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Abstract

Experimental and analytical effort shows that use of advanced turboprop (propfan) propulsion instead of conventional turbofans in the older narrow-body airline fleet could reduce fuel consumption for this type of aircraft by up to 50 percent. The NASA Advanced Turboprop (ATP) program was formulated to address the key technologies required for these new thin, swept-blade propeller concepts. A NASA, industry, and university team was assembled to develop and validate applicable new design codes and prove by ground and flight test the viability of these new propeller concepts. This paper presents some of the history of the ATP project, an overview of some of the issues and summarizes the technology developed to make advanced propellers viable in the high-subsonic cruise speed application. The ATP program was awarded the prestigious Robert J. Collier Trophy for the greatest achievement in aeronautics and astronautics in America in 1987.

I. Introduction

Until the advent of the ATP program in 1978, propeller technology development had stopped in the mid-1950's. This 20-year gap in development occurred because we did not know how to build prop blades with the combined structural and aerodynamic characteristics to operate reliably and efficiently at the high subsonic cruise speeds obtained by the turbojets then being introduced into commercial service.

Although propellers were more fuel efficient than turbojets and turbofans, propulsion development was largely concentrated on improvements to the turbojet during this era of cheap fuel.

Perspectives changed beginning in 1973, as a result of the Middle East oil embargo. Fuel costs escalated and by 1980 had gone from about one-quarter to more than half of direct operating costs, as illustrated in Fig. 1.

In January 1975, the U.S. Senate Committee on Aeronautical and Space Science requested that NASA develop a program to address the fuel crisis.[1,2] In response, NASA formed an inter-agency task force that considered many potential fuel-saving concepts. They proposed the Aircraft Energy Efficiency (ACEE) program, which included three propulsion projects managed by NASA Lewis. One of these, strongly advocated by NASA Lewis and Hamilton Standard Division of United Technologies, was to develop advanced turboprops which could overcome the high-speed compressibility losses of conventional propeller designs.

NASA conducted several system studies which showed that advanced propellers could have propulsive efficiencies about 1.3 times as high as those of equivalent turbofans at cruise speeds of Mach 0.8. These results are illustrated in Fig. 2. Also shown is an artist's rendition of the new advanced turboprop, or "propfan" concept and, for comparison, the old four-bladed prop typical of those used on the Lockheed Electra. Although the old turboprops were fuel efficient up to airspeeds of slightly over Mach 0.6, they experience a rapid increase in compressibility losses beyond these speeds due to their thick, unswept, large-diameter blades. Their propulsive efficiency is much higher than that of high bypass turbofans at speeds up to Mach 0.6+ because in generating thrust a prop imparts only a small increase in axial velocity to a large mass flow of air, thereby reducing kinetic energy losses in the discharge flow. The advanced turboprop uses very thin, highly swept blades to reduce both compressibility losses and propeller noise during high-speed cruise. High disk power loadings (SHP/D^2) at least double that of the Lockheed Electra are required for high-speed cruise and are achieved by increasing the number of blades and lengthening blade chord. Counterrotating blade designs can be used to provide still higher disk power loadings and eliminate some of the exit "swirl" losses associated with single-rotation propellers. Installed propulsive efficiencies roughly equivalent to those achieved with the old Electra technology can be extended to the Mach 0.8 regime with advanced propellers. The advanced turboprop produces fuel savings conservatively estimated at about 30 percent due to the improved propulsive efficiency of the propfan and 50 percent better overall with core engine improvements included.[2] To illustrate the impact of such a savings on today's U.S. airline fleet, if advanced turboprops were substituted for the turbofans used in only the narrow-body 727's, 737's, DC9's, and MD80's, about 2.5 billion gallons of fuel would be saved per year.[3]

II. ATP Programmatic Objectives and Plans

NASA formally began the Advanced Turboprop (ATP) project in 1978 with the overall objective of validating key technologies required for both single- and counterrotating propfans in Mach 0.65 to 0.85 applications. Project goals were to verify projected propfan performance and fuel savings benefits; to verify the structural integrity of these radically different blade designs under actual operating conditions; to establish passenger comfort levels (i.e., cabin noise and vibration) approaching those in modern turbofan-powered airliners; and to verify that propfan-powered aircraft could meet the airport and community noise standards specified by U.S. Federal Air Regulations (FAR-36). The project plan projected system technology readiness by the late 1980's.

The NASA ATP project was organized in such a way that technical issues were first resolved through wind tunnel testing of small-scale models before more costly large-scale ground and flight testing. The early years of ATP (prior to 1980)

provided the enabling technology via small-scale testing and design code development to establish the feasibility of the propfan. A fundamental data base of design, analysis, and testing techniques was developed. A large-scale technology integration phase then drew from this knowledge to design, fabricate, and ground test large-scale propfan systems. The large-scale effort was needed to eliminate uncertainties concerning the scale-up of structural and acoustic data obtained with wind tunnel models.[1] Flight research testing of large-scale propfan propulsion systems was initiated in 1986 to verify blade structural integrity, to determine cabin comfort and ground noise levels, to provide scaling comparisons with model tunnel data, and to validate computer analyses. As these tests were completed, an extensive analysis effort was implemented to assess the data acquired.

From the beginning of the ATP project, a systems approach which considered the entire aircraft was used in designing the propulsion system, as shown in Fig. 3. This included elements such as the propeller and the nacelle, the drive system, installation aerodynamics, and the aircraft interior and community environments and the effect of these elements on meeting the goals of reduced fuel consumption, low operating costs, and passenger acceptance. This approach followed the logic path illustrated in Fig. 4. The sequence started with analyses and systems studies and proceeded to design code development based on scale-model wind tunnel tests or component tests. Finally, large-scale systems were designed, built, and tested both on the ground and in flight as proof of the concept. This approach was used in the three propfan configurational areas shown: single rotation, gearless counterrotation, and geared counterrotation.

The technical expertise of all three NASA aeronautical research centers (Lewis, Langley, and Ames), more than 40 contracts distributed over the majority of the U.S. aircraft industry, and over 15 university grants were required to complete the project. Major contracts were awarded to General Electric on the Unducted Fan (UDF), Hamilton Standard on the Large-Scale Advanced Propfan (LAP), and Lockheed-Georgia on the Propfan Test Assessment (PTA). In addition to NASA-sponsored research, a significant independent industrial research and development effort was applied to develop these new concepts. Beginning in August 1986, the advanced turboprop propulsion concept was proven by three flight programs using large-scale hardware (Fig. 5). The NASA-General Electric-Boeing flight test and the General Electric-McDonnell Douglas flight test used the Unducted Fan as a proof-of-concept demonstrator for the gearless counterrotating concept. The NASA/Lockheed-Georgia Propfan Test Assessment verified the structural integrity and acoustic characteristics of the single-rotating LAP propfan built by Hamilton Standard. On the basis of the success of these tests and previous scale-model work, Pratt & Whitney-Allison built a geared propulsion system with Hamilton Standard counter-rotating propellers that they plan to fly on the MD-80 in late 1988.

The three top pictures of Fig. 6 illustrate the post-flight test NASA generic propeller research program of analysis and scale model wind tunnel tests leading to design validation and verification of aerodynamic, acoustic, and structural codes. This on-going research program will make extensive use of the previously acquired ATP database. Advanced concepts of a single-rotation propfan with stator vane swirl recovery and a high-bypass-ratio ducted-fan configuration are illustrated in the two bottom drawings. While future ducted props will not have the efficiency of unducted propfans they may be more suitable for "packaging" on large aircraft such as the Boeing 747.

III. Single-Rotation Systems

The first 2-ft-diameter propfan single-rotation model, designated SR-1 and incorporating eight thin, swept blades, was developed by NASA and Hamilton Standard in 1976.[2]

When tested in a wind tunnel, the SR-1 achieved an efficiency of 77 percent at Mach 0.8. The model blades were stable even when an attempt was made to force flutter. Encouraged by this but still needing to fully understand the efficiency and noise potential of the propfan, several more models were designed and tested.

One was an improved version, the SR-1M, with a modified spanwise twist to better distribute the blade loading, which resulted in a 1-point gain in overall efficiency. Another model, the straight-bladed SR-2, was designed to provide a baseline for comparison. Its efficiency was slightly less than 76 percent at Mach 0.8. The subsequent SR-3 model, which incorporated 45° of sweep for both aerodynamic and acoustic purposes, achieved an efficiency of nearly 79 percent. Some of the early blade models that were wind-tunnel tested are shown in Fig. 7.

The performance gains (i.e., incremental gains in propeller efficiency) and noise reductions due to increased blade sweep for the SR-2, SR-1M and SR-3 configurations are summarized in the plot of measured data in Fig. 8.[2] All three blades were very thin but varied in amount of tip sweep from 0° to 45°. All three of these configurations are compared at their design point condition of Mach 0.8, disk power loading of 37.5 SHP/D^2, and tip speed of 800 ft/sec. It is clear that both performance and acoustics benefit as blade sweep is increased. These model tests eventually led to the wind tunnel test of the SR-7A model, which is an aeroelastically scaled 2-ft model of the 9-ft propfan flight tested later in the PTA program.[4]

Net efficiencies of the propeller models are shown as a function of Mach number in Fig. 9.[5] At Mach 0.80 the SR-7A propfan has the highest measured propeller efficiency - 79.3 percent. The performance of the SR-2 propeller is lower than that of the others because of its unswept blade design. The number of blades and amount of tip sweep are tabulated below for each of these models.

Design	Number of blades	Sweep angle, deg
SR-7A	8	41
SR-6	10	40
SR-3	8	45
SR-1M	8	30
SR-2	8	0

Near-field acoustic results were recently obtained with the SR-7A model at high-speed cruise conditions in the NASA Lewis 8x6 ft tunnel, as shown in Fig. 10. Peak fundamental tone levels are plotted against helical tip Mach number (i.e., the blade relative Mach number) for three loading levels.[6] The data show that fundamental tone levels may peak, level off, or decrease beyond a helical tip speed of Mach 1.1, depending on loading.

Although the effect of increasing blade sweep is positive in terms of improvements to propulsive efficiency and acoustics at high flight speeds, the structural and aeroelastic design becomes more difficult. One structural concern relates to steady state stress levels due to centrifugal and steady aerodynamic loads. Another relates to an aeroelastic instability phenomenon called flutter which can occur in response to forced excitations caused by unsteady, unsymmetrical airflows produced by gusts, upwash from the wing, and airframe-induced flow field distortions. The presently ill-defined boundary for high-speed classical flutter will occur at increasingly reduced flight speeds as blade tip sweep is increased, all other things (e.g., materials, construction) remaining equal. Avoidance of this flutter boundary is one reason why the sweep of the SR-7 was limited to 41° at the tip.

An experimental and analytical research program is being conducted to better understand the flutter and forced response characteristics of advanced high-speed propellers. A comparison of measured and calculated flutter boundaries for a propfan model designed to flutter is shown in Fig. 11.[7,8] The theoretical results, from the NASA Lewis-developed ASTROP3 analysis, include the effects of centrifugal loads and steady-state, three-dimensional air loads. The analysis does reasonably well in predicting the flutter speeds and slopes of the boundaries. However, the difference between the calculated and measured flutter Mach numbers is greater for four blades than for eight blades. This implies that the theory is overcorrecting for the decrease in the aerodynamic cascade effect with four blades.

Euler code solutions have recently been developed to describe the unsteady, three-dimensional flow field generated with advanced propeller designs.[9] A graphical display of the blade pressure contours from this analysis is shown in Fig. 12 for an SR-3 propfan in regions where the flow is supersonic when the axis of rotation is tilted upward 4° from the Mach 0.8 free-stream flow. The downward moving blades (on the right in the figure) experience the highest loadings, whereas the upward moving blades experience some unloading due to the alternating alignment of the upward component of the free-stream velocity with the upward and downward blade rotational velocity vectors. Pressure contours for the blades at the top and bottom of the rotation are relatively unaffected by the tilt of the rotational axis because at these positions the rotational velocity component is perpendicular to the upward free-stream component.

Cabin noise and vibration levels with past turboprops has been less favorable than with turbofans. To achieve a cabin environment with propfans that is comparable to current turbofan transports, a reduction of 25 to 30 dB beyond the capacity of a bare-wall untreated cabin is likely to be required for a wing-mount installation. NASA Langley Research Center has been involved in several ATP noise reduction activities, including the evaluation of advanced cabin sidewall concepts. A Langley/Lockheed-California effort has led to the development of an advanced cabin wall acoustic treatment utilizing Helmholtz resonators tuned to the fundamental blade passing frequency. This concept was flight tested in the PTA program and is discussed later in connection with those flight tests.

Under NASA sponsorship, Hamilton Standard initiated the design of a Large-Scale Advanced Propeller (LAP) in 1982. The resulting 9-ft diameter SR-7 propfan design incorporates the spar-shell type of blade construction illustrated in Fig. 13.[1] All new Hamilton Standard straight-bladed commuter aircraft propellers use a similar spar-shell type of construction which has proven to be very safe, reliable, and lightweight. The FOD problems inherent in earlier solid aluminum blades are avoided by protecting the single load-bearing spar with an aerodynamically-shaped fiberglass shell. This construction technique, however, was unproven for the thin, swept, LAP blade design which is subjected to complex nonlinear deflections under load. The possibility of high-speed classical flutter and the need to verify the design codes that were used reinforced the need for large-scale fabrication and flight testing.

The 9-ft diameter size for the LAP rotor assembly was selected as the minimum size that would permit a realistically-scaled blade cross section with the minimum allowable shell gauge thickness. Existing drive system capability was limited to about 3000 SHP at the Mach 0.8/35 000 ft design point and also dictated a diameter of about 9 ft if disk power loadings (SHP/D^2) in the desired desired 30 to 40 SHP/ft^2 range were to be obtained.

A LAP static rotor test was completed in late 1985 at a Wright-Patterson Air Force Base facility, as shown in Fig. 14, using a facility electric drive motor.[10] Forty-six strain gages, some of which can be seen in this photo, were installed on the LAP during manufacture. Of this total, 30 strain gages were connected through slip rings to a data system and continuously recorded during propfan operation while the remainder were spares which could be used in the event of a malfunction of one of the primary gages. This instrumentation and data system were retained throughout the LAP and follow-on PTA testing. In early 1986, the LAP was installed in France's Modane wind tunnel to verify blade structural integrity at speeds up to Mach 0.83. A second Modane tunnel entry occurred in early 1987 to acquire blade steady and unsteady pressure data for verifying and improving aerodynamic prediction codes. Figure 15 depicts

the second LAP Modane entry, blade pressure instrumentation location schematics for two blades specially instrumented for this particular test, and also one of the two completed propfans delivered to the PTA project.

The two-bladed version of the eight-blade propfan shown in Fig. 15 was used in some of the Modane testing because of the limited facility power available to drive the propeller. In this way the propeller could be operated at a reasonable power loading per blade. The large size of this propeller allowed much more detailed blade pressure measurements than could be obtained on the 2-ft diameter models tested previously.

Prior to flight test, several scale-model tests of the PTA airplane were conducted in NASA wind tunnels in the interest of flight safety and to obtain data for validating aerodynamic prediction codes. Both a 1/9-scale airplane aeroelastic model[11] and a 1/9-scale aerodynamic/stability and control model[12] were built and tested. The results from both models showed excellent agreement with analytical predictions. A rake survey of the flowfield at the propfan plane was also conducted with a modified version of the PTA aerodynamic model to verify the flowfield prediction code.[13] The predicted flowfield at the various flight test conditions was used as a correlation parameter for measured propfan stress.

A ground static test of the entire PTA propulsion system - including the strain-gage-instrumented propfan, engine/gearbox, and forward nacelle - was conducted in the spring of 1986 at an outdoor thrust stand (Fig. 16).[14] Over 50 hr of extensive testing was accomplished, with essentially flawless system operation and with blade stresses at a level somewhat below those seen at the previous static rotor test. In neither of these static tests was there any evidence of blade flutter and stresses were low except at very high blade angles where buffeting characteristic of separated flow was sometimes indicated.

After G-II aircraft modifications to install the propfan propulsion system on the left wing and the subsequent ground checkout testing, PTA flight testing began in the spring of 1987.[15] Some photos of the PTA flight testing are shown in Fig. 17. One unique feature of the PTA design was the variable tilt nacelle which allowed the forward portion of the nacelle to be tilted up or down so that blade stresses could be assessed as a function of inflow angle. The PTA flight test program was performed to verify LAP structural integrity and characterize LAP acoustics both outside and inside the cabin as well as on the ground. Data were obtained over a flight envelope extending from just above low-speed stall to Mach 0.89 and at altitudes from 800 to 40 000 ft.

A total of up to 613 acoustic, g-loading, pressure, strain, temperature, and miscellaneous operating parameters were recorded onboard the aircraft at each of almost 900 completed test runs during the PTA research flight tests. The PTA flight test program involved more than 133 hr of flight time over a total of 73 flights.

Initial flight noise test data agree favorably with both scaled-up NASA wind tunnel data and predictions obtained with an analytical code.[15] Comparative maximum noise data along the fuselage exterior are presented at axial locations fore and aft of the plane of rotation in Fig. 18. A maximum sound pressure level of 147 dB was measured at the fundamental blade passing tone of 225 Hz. The measured local noise reduction at an adjacent location inside the bare-wall cabin was 25 dB.

Subsequent to the basic bare-wall cabin flight test effort, a 10-ft section of the PTA cabin was cleared for acquiring data with an advanced cabin acoustic treatment in early 1988. The treated enclosure, located fore and aft of the propfan plane of rotation, consisted of tuned Helmholtz resonator wall panels attached to a framework mounted to the cabin floor through vibration isolators. Preliminary results obtained from the 31 cabin interior microphones indicate that noise levels 25 to 30 dB below that of the bare-wall cabin were obtained. This is the approximate level required for comparability with existing turbofan-powered airliners.

The PTA flight test effort was concluded in March 1988. Although some preliminary results are available, because of the massive quantity of data to be analyzed the final results will not be available until October 1988. It is clear, however, that these flights, as intended, verified propfan structural integrity. There was no evidence of flutter anywhere in the flight regime and blade stressing was in good agreement with predictions. Measured blade stresses were within limits established by Hamilton Standard for infinite life. Preliminary acoustic data analysis indicates that magnitudes and trends are generally as predicted with propfan noise slightly lower than predicted. It appears that advanced cabin acoustic treatments can reduce interior noise to acceptable levels and that FAR36 (stage 3) airport community standards can be met when data are extrapolated to a product design.

IV. Gearless Counterrotation Systems

Counterrotation propeller systems are of interest because of their potential to further enhance propulsive efficiency by reducing or eliminating the swirl component of the discharge velocity. In order to generate propulsive thrust, a propeller must take essentially axial flow and turn it to do work, in much the same way that an airplane wing must turn the flow slightly downward in order to generate upward lift. The result with a single-rotation propeller is that the discharge flow must have a nonaxial rotational component of perhaps several degrees, depending on disk loading and tip speed. A decrease in net thrust (and, hence, propulsive efficiency) results from this nonaxial, or "swirl," velocity component since the total change in momentum is not in the axial direction, as it ideally should be for the production of thrust. The swirl losses for an isolated single-rotation propfan at Mach 0.8 design point operating conditions are typically equivalent to about eight points in efficiency. These losses can be reduced or eliminated by using counter-rotation as a swirl recovery technique. With counter-rotation, the second, or aft stage, propeller rotating in the opposite direction returns the flow to the axial direction as it performs its work.

By 1983 General Electric became convinced that a gearless counterrotating Unducted Fan (UDF) engine would be a viable fuel-saving alternative to the turbofan. Rather than venture into the uncertain area of gearbox design for a 20 000 hp-class engine, GE chose to eliminate the gearbox by using a counterrotating power turbine to directly drive the props.[2,16] A cutaway of this concept is shown in Fig. 19. The gas generator ahead of the power turbine in this concept demonstrator is not mechanically linked to the power turbine, which is driven solely by hot exhaust gas.

The UDF prop blades were designed for an overall disk power loading almost twice as great as that of the single-rotation designs. Hub-to-tip radius ratio of these blades is about 75 percent higher than that typical of geared designs in order to accommodate the large-diameter power turbine. The large turbine diameter is required for power generation and compensates for the low rpm restraint imposed by the prop tip speed limit. Except for a set of inlet and outlet guide vanes, this 12-stage power turbine is unique in that it has no stator vanes between the alternating opposite-rotation blade rows.

The UDF blade structural design chosen by GE is somewhat different from that used by Hamilton Standard for the LAP blades. The LAP blade consisted of a full-length structural spar and a fiberglass shell; the shell of the UDF blade, in contrast, is the structural element and the spar is used for attachment.[2] The blades have a half-span titanium spar covered with an aerodynamic shell of epoxy-bonded carbon-fiber/fiberglass plies, as shown in Fig. 20. The plies are oriented in such a way as to tune the directional stiffness for blade shape control, strength, and aeromechanical stability. The blade design also includes a nickel leading-edge sheath and polyurethane film bonded to the outer shell to provide additional protection. Blade design and construction is basically the same for both forward and aft rows.

The NASA Lewis counterrotation pusher propeller test rig shown with a UDF blade configuration in the 8- by 6-Ft Wind Tunnel in Fig. 21 was one of three built by GE for model blade testing.[17] The other two were used at Boeing and GE. Performance, flowfield, and acoustic measurements were made during this testing. The UDF model blade configurations tested at NASA Lewis are shown in Fig. 22. The designs differed in tip sweep, planform shape, airfoil camber, and included one case with a significantly shortened aft rotor. The planform shapes for most forward and aft rotors were very similar. These blades were designed and built by General Electric. Net efficiences for the F7-A7 blade configuration are shown in Fig. 23 as a function of cruise speed for three power loadings.[5] At Mach 0.72 design conditions, efficiency is strongly affected by loading, but as Mach number increases, compressibility losses dominate and efficiencies fall off essentially independent of loading.

General Electric used NASA design codes for propeller ply design, flutter analysis, aerodynamic design, and noise prediction. Model rig data was also used by GE to modify, improve, and verify their own inhouse codes.

Both steady and unsteady flow prediction codes have been developed for counterrotation propellers. Figure 24 shows the three-dimensional image of the UDF pressure distribution generated with a NASA Lewis-developed Euler prediction code.[18] The coupling between rows is done in a circumferentially-averaged sense which does not consider blade-wake interaction effects. The pressure distribution is shown on the nacelle, blade surfaces, and on a flow cross section downstream of the aft rotor. An unsteady Euler code solution has also been applied to the F7-A7 UDF configuration to obtain the full unsteady three-dimensional solution for the flow field.[9] Pressure contours at a particular instant in time are shown in Fig. 25 at a plane just downstream of the aft blade row. The low pressure islands shown are the result of tip vortex shedding.

The UDF demonstrator engine is shown during ground static testing at GE's Peebles, Ohio outdoor test facility in the top photo of Fig. 26. After completing this ground testing, the UDF demonstrator was installed on a Boeing 727 airplane for flight testing in August 1986. The engine was later installed on an MD-80 in May 1987 for a Douglas flight test program. These flight test configurations are shown in the two bottom photos of Fig. 26. The UDF was substituted for the right-hand JT8D powerplant on the 727 and for the left-hand JT8D on the MD-80 airplane.

Fundamental tone directivities for the F7-A7 blade combination, the proof-of-concept UDF configuration, are shown in Fig. 27 for scaled wind tunnel model data and full-scale flight data obtained by the instrumented NASA Lewis Learjet in formation flights with the UDF-powered 727.[5] There is excellent agreement among the model wind-tunnel measurements, full-scale flight data, and prediction at most sideline angles, although the wind tunnel data appear to be somewhat high at forward angles.

V. Geared Counterrotation Systems

NASA has also sponsored research leading to the development of a more conventional geared counterrotating propfan system using blade technology which is basically an extension of that pioneered in the LAP single-rotation propfan. As part of this effort, Allison Gas Turbine Division of General Motors designed, fabricated, and rig-tested a 13 000 shp-class advanced in-line differential planetary counterrotation gearbox.[15] Ease of maintainability, high (over 99 percent) mechanical efficiency, and a high durability were of paramount importance in this gearbox design. Allison used the results of these tests in developing the technically similar flightweight gearbox for the Pratt & Whitney-Allison/Douglas 578DX/MD-80 flight test program.

The Hamilton Standard CRP-X1 propeller model (Fig. 28) was evaluated in wind tunnels for performance and flow field data, blade stresses, and acoustics.[19,20] At the Mach 0.8 design power loading, a net efficiency improvement of ~6 percent was obtained over the analogous SR-7A single-rotation model. The counterrotation propfan design used in the MD-80/578DX flight test is based on the technology of the CRP-X1 model and the earlier SR-7.

Flow characteristics of these types of counterrotation propellers have also been predicted with analytical codes. One such example, shown in Fig. 29, is the analytically simulated flow visualization of an off-design vortex shedding phenomenon with the CRP-X1 model design. If not accounted for in analytical models, errors in predicted performance and noise will occur. The results shown are from an Euler code developed at NASA Lewis and run to simulate takeoff with a high blade incidence angle.[18]

Levels of the first five harmonics of single-rotation and counterrotation propeller noise, based on Hamilton Standard model test data, are shown in Fig. 30 at three axial locations in the far field.[20] The single rotation tone levels have been adjusted upward 3 dB to compare the equivalent of two independent propellers with the CRP-X1 counterrotation configuration. Single and counterrotation fundamental tones are then roughly equal, but the counterrotation higher harmonics are dramatically higher at all locations due to the unsteady aerodynamic interactions between blade rows. The high fore and aft harmonic levels must be dealt with to achieve acceptable counterrotation community noise levels.

VI. Future Research

In future work, NASA will attempt to achieve some of the swirl recovery benefit of counterrotation without the additional complexity and noise, by using swirl recovery vanes with a single-rotation propfan model (Fig. 6, bottom left).

Future NASA research effort will also be directed toward the ducted propeller, which was discussed briefly in connection with Fig. 6. Ducted props are more easily integrated into the design of large long-range aircraft than unducted props because they are more compact than unducted propfans. Underwing installations of propfans on large heavy aircraft are unlikely because the large tip diameter requirements will cause ground clearance problems. There are several technical issues which must be addressed with regard to ducted props.[5] At cruise, the drag of the large-diameter thin cowl must be kept low while maintaining acceptable near-field noise levels. Tradeoffs between propeller and fan aerodynamic design methods are required to arrive at the optimum combination of ducted prop design parameters. At low-speed conditions, far-field noise in the community; tip flow separation and blade stresses with a short, thin cowl at high angles of attack; and reverse thrust operation are technical issues requiring further investigation.

VII. Concluding Remarks

Propfan technology in little more than a decade has evolved from a fuel saving idea, through the test of small-scale models, to the current flight test of large-scale complete propulsion systems. In 1987 the advanced turboprop propulsion concept was proven by three flight programs using large-scale hardware. The NASA/General Electric/Boeing flight test and the General Electric/McDonnell Douglas flight test used the Unducted Fan demonstrator to prove the gearless counter-rotating concept. The NASA/Lockheed-Georgia Propfan Test Assessment flight test used a propfan built by Hamilton Standard to prove the geared single-rotation concept and to compare large-scale flight data with an extensive wind tunnel model data base. On the basis of the success of these tests and previous scale-model work, Pratt & Whitney - Allison built a geared counter-rotating propulsion system that they plan to fly this year on the MD-80 aircraft. It is clear from these efforts that much of the predicted fuel savings potential can be realized with designs which maintain their structural integrity in flight. Preliminary indications are that propfan noise trends are also generally as predicted and that acoustic treatments can be designed to satisfactorily attenuate cabin noise.

Because of the fuel savings potential for this concept, which can be implemented without any sacrifice in the speed and comfort we have grown to expect, it is anticipated that this technology will lead to a whole new generation of propfan-powered aircraft - both civil and military.

Although more work is yet to be done in ATP data acquisition and analysis, the rapidly expanding database already in existence will permit technically sound marketing decisions to be made by industry in the deployment of private investment capital. Early candidate production aircraft are now on the drawing boards. The Lewis Research Center and the entire NASA/Industry Advanced Turboprop Team were cited in the Collier Trophy award (Fig. 31) presented in May 1988, by the National Aeronautic Association for this work which they consider as the greatest achievement in aeronautics or astronautics in America demonstrated by actual use in the previous year.

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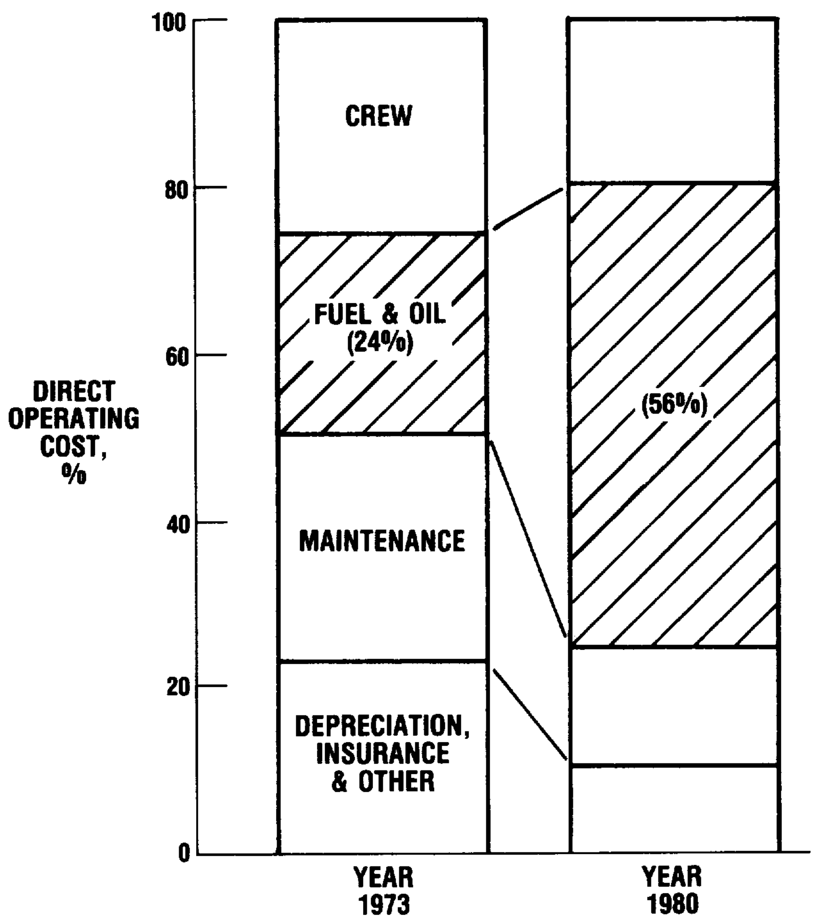

FIGURE 1. - FUEL COST ESCALATION AS PERCENTAGE OF DIRECT OPERATING COST. U.S. DOMESTIC TRUNK OPERATIONS. (CAB DATA)

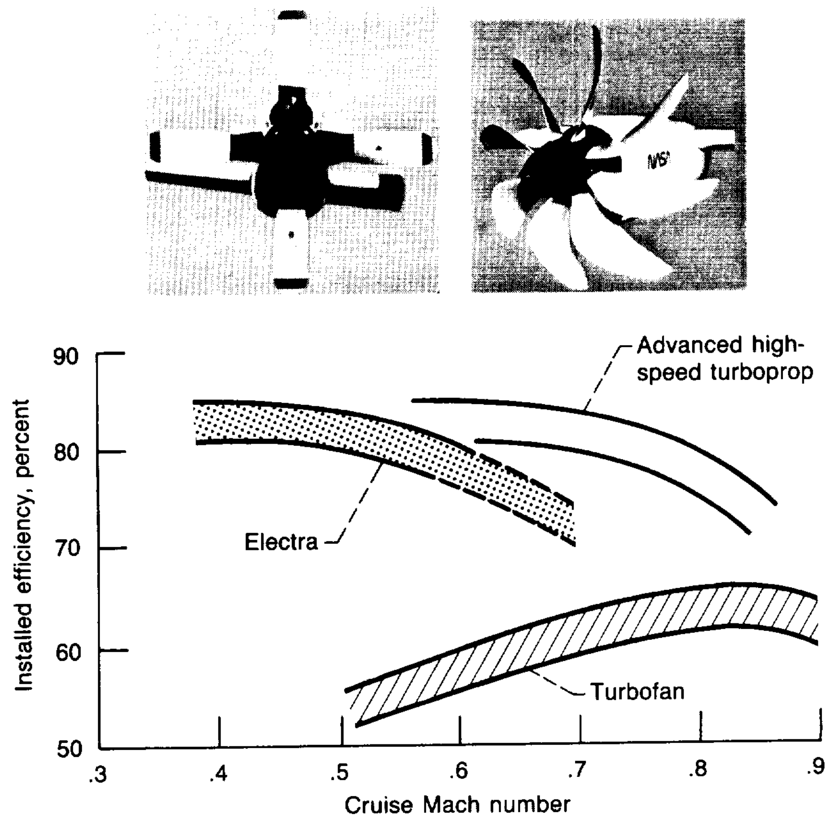

FIGURE 2. - EFFICIENCY TRENDS FOR TURBOPROP AND TURBOFAN ENGINES.

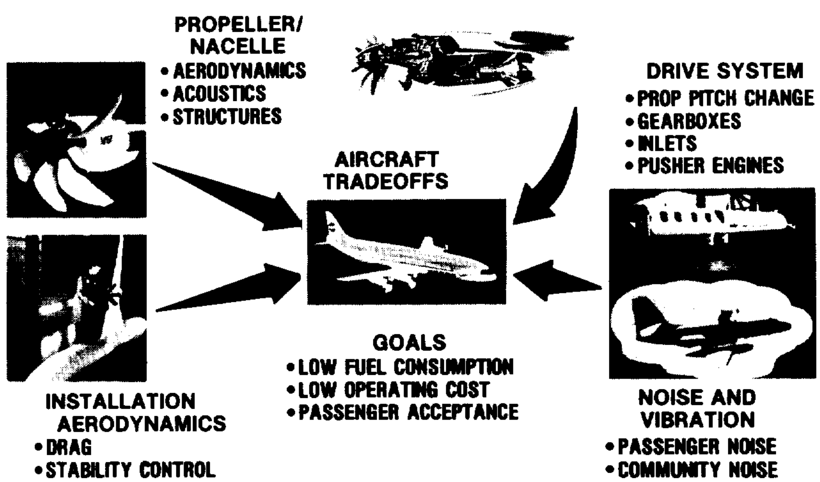

FIGURE 3. - ELEMENTS NEEDED TO DEVELOP ADVANCED TURBOPROP AIRCRAFT.

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FIGURE 4. - NASA/INDUSTRY ADVANCED TURBOPROP (ATP) PROGRAM.

PTA/GULFSTREAM GII

UDF/BOEING 727

**UDF/MD-80 AND
578DX/MD-80**

FIGURE 5. - FLIGHT TESTING OF ADVANCED TURBOPROPS.

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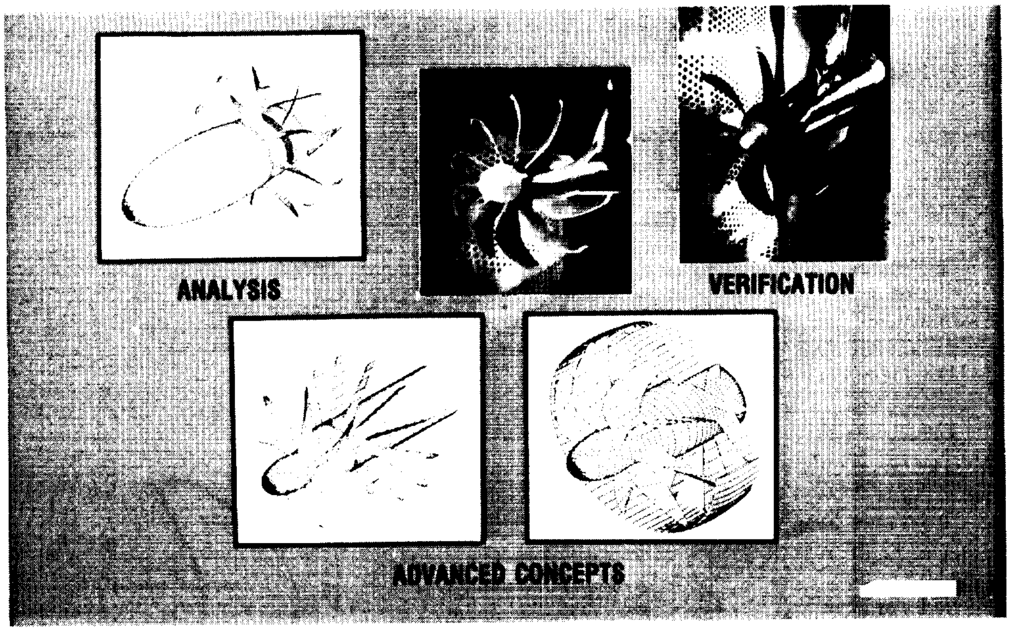

FIGURE 6. - POST-FLIGHT-TEST AREAS OF ON-GOING PROPELLER RESEARCH AT NASA LEWIS RESEARCH CENTER.

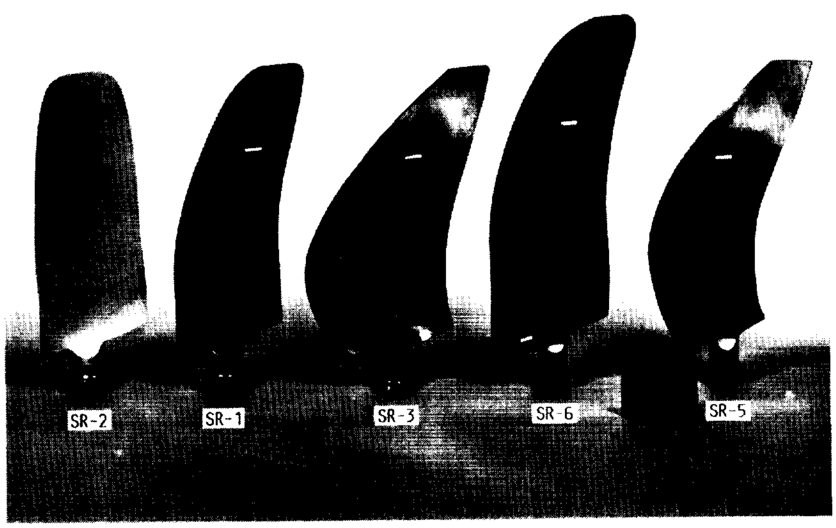

FIGURE 7. - ADVANCED PROPELLER BLADE WIND TUNNEL MODELS.

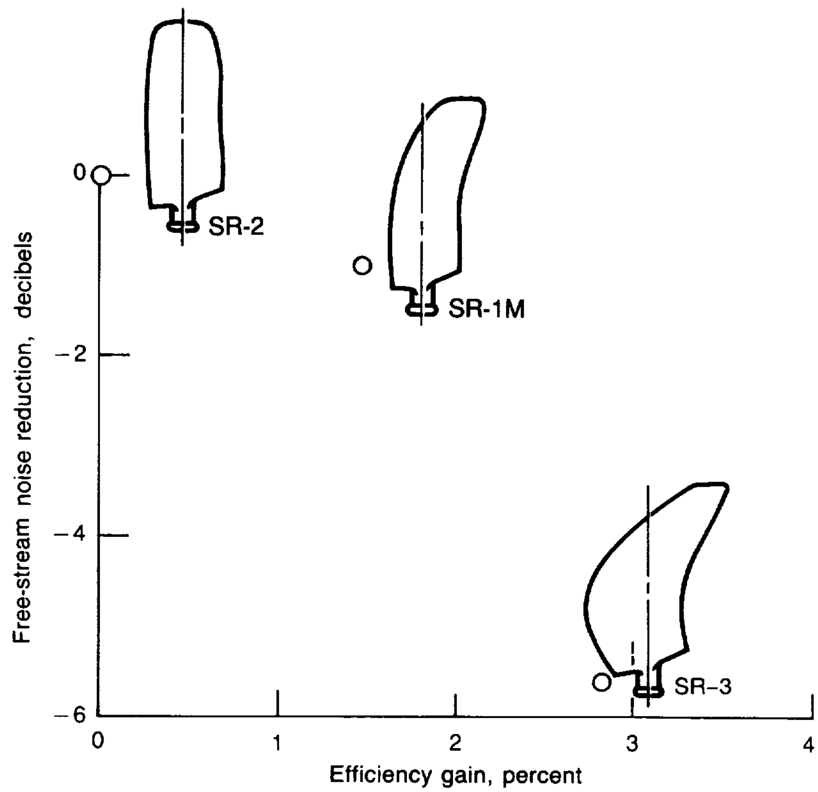

FIGURE 8. - NOISE AND PERFORMANCE CHARACTERISTICS OF PROPELLER MODELS AT MACH 0.8, 37.5 SHP/FT^2 DISK POWER LOADING, AND 800 FT/SEC TIP SPEED.

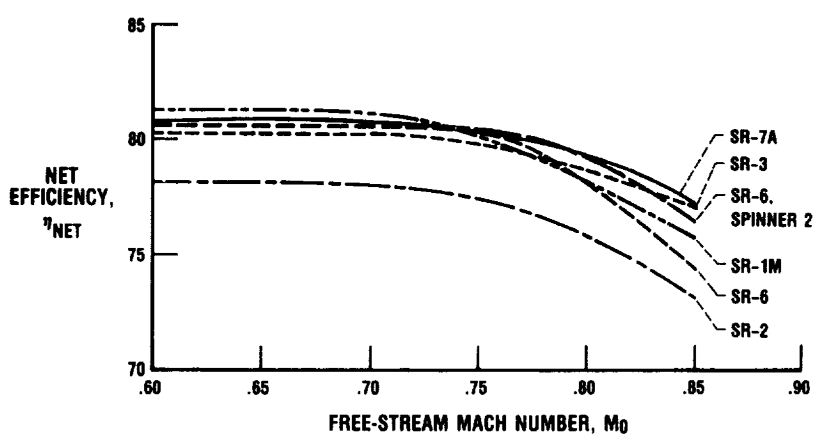

FIGURE 9. - SINGLE-ROTATION PROPELLER PERFORMANCE.

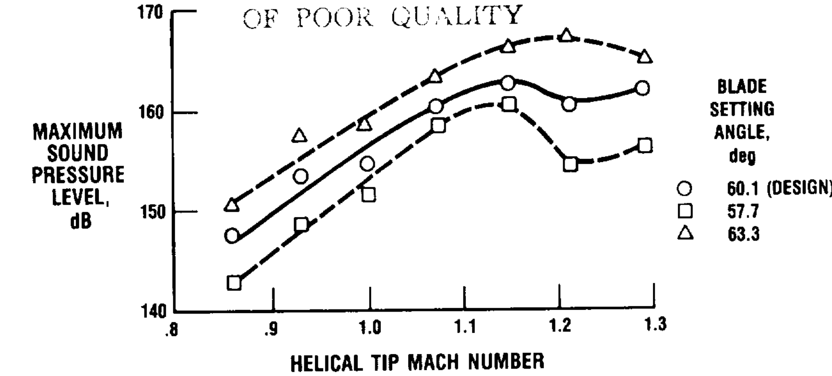

FIGURE 10. - SR-7 PEAK BLADE PASSING TONE VARIATION WITH HELICAL TIP MACH NUMBER.

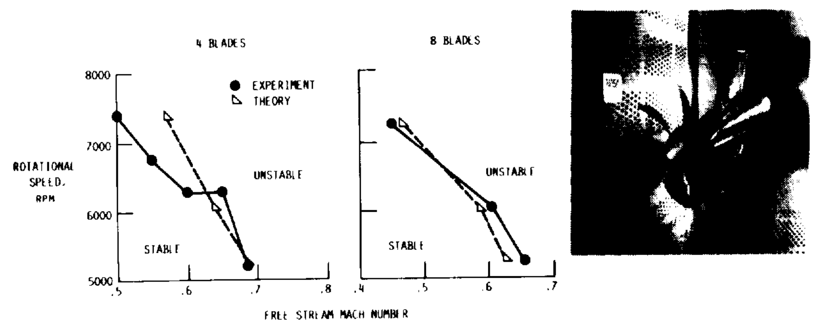

FIGURE 11. - COMPARISON OF MEASURED AND CALCULATED FLUTTER BOUNDARIES WITH SR3C-X2 PROPFAN MODEL.

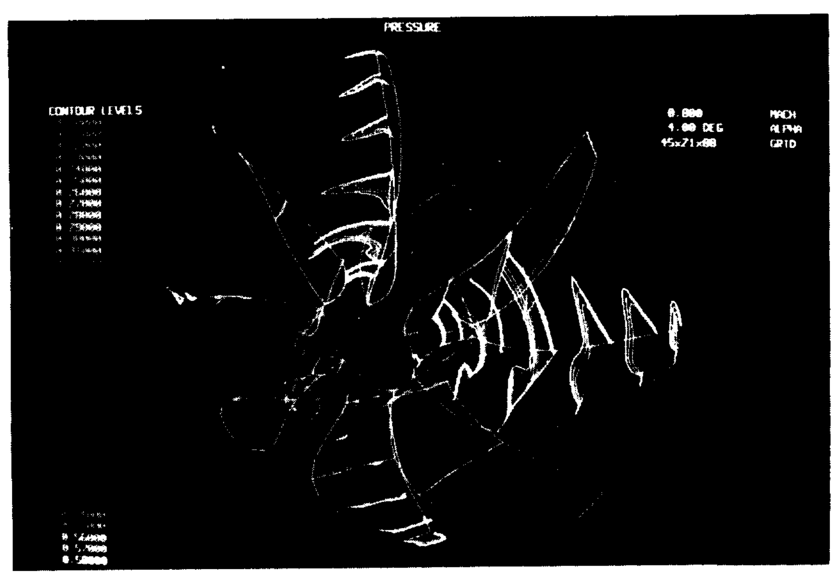

FIGURE 12. - UNSTEADY THREE-DIMENSIONAL EULER CODE SOLUTION AT MACH 0.8 WITH SR-3 PROPFAN AXIS AT 4^{o} ANGLE OF ATTACK.

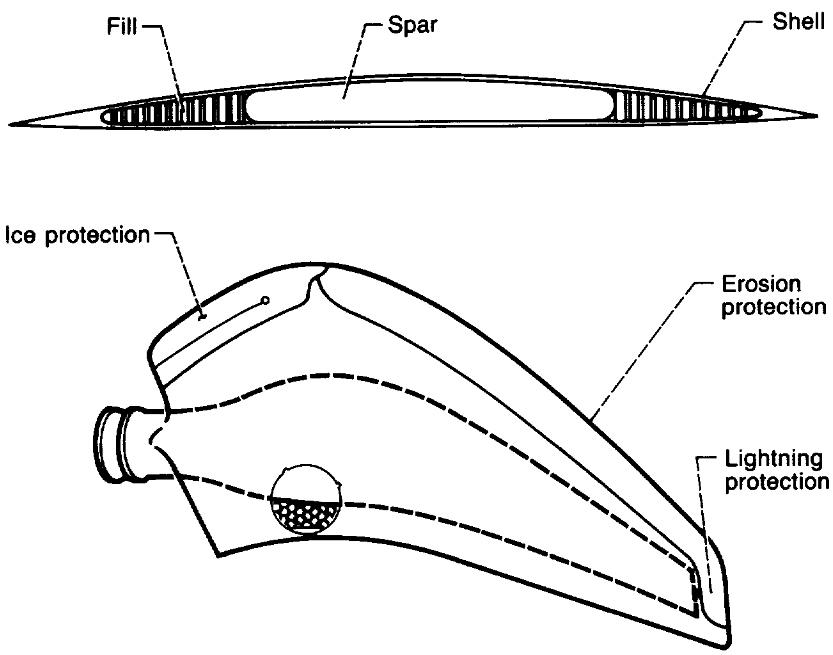

FIGURE 13. - SCHEMATIC OF THE SPAR-SHELL BLADE CONSTRUCTION CONCEPT USED FOR THE LAP.

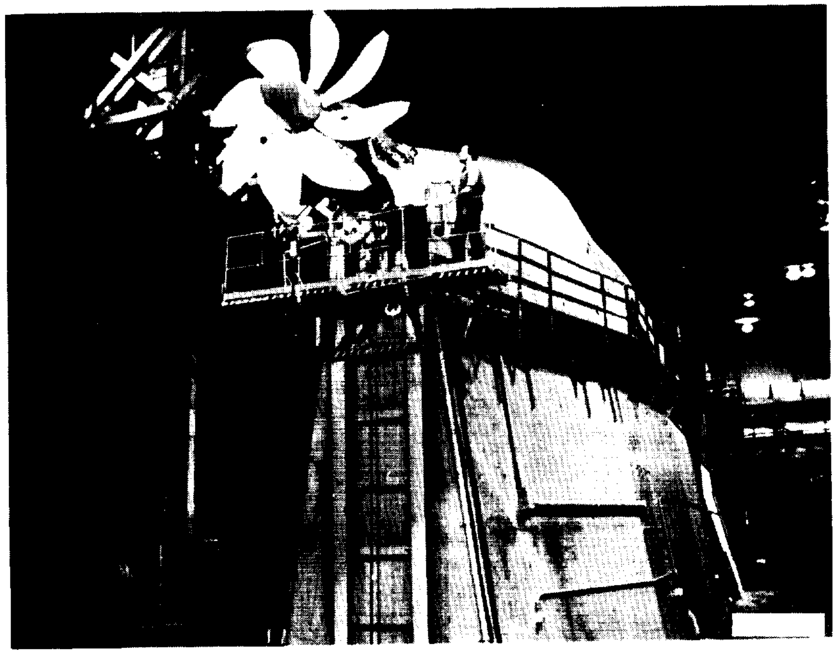

FIGURE 14. - LAP STATIC ROTOR TEST AT WRIGHT-PATTERSON AIR FORCE BASE FACILITY.

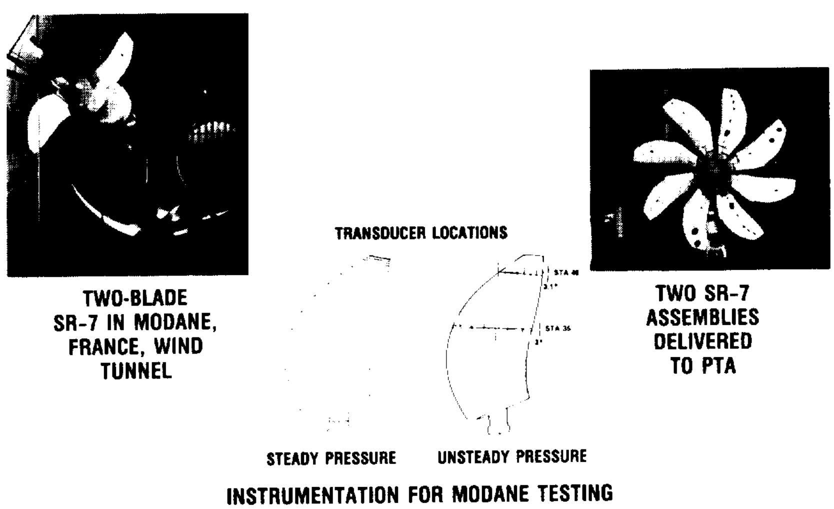

FIGURE 15. - NASA LARGE-SCALE ADVANCED PROPELLER (LAP) PROJECT HIGHLIGHTS.

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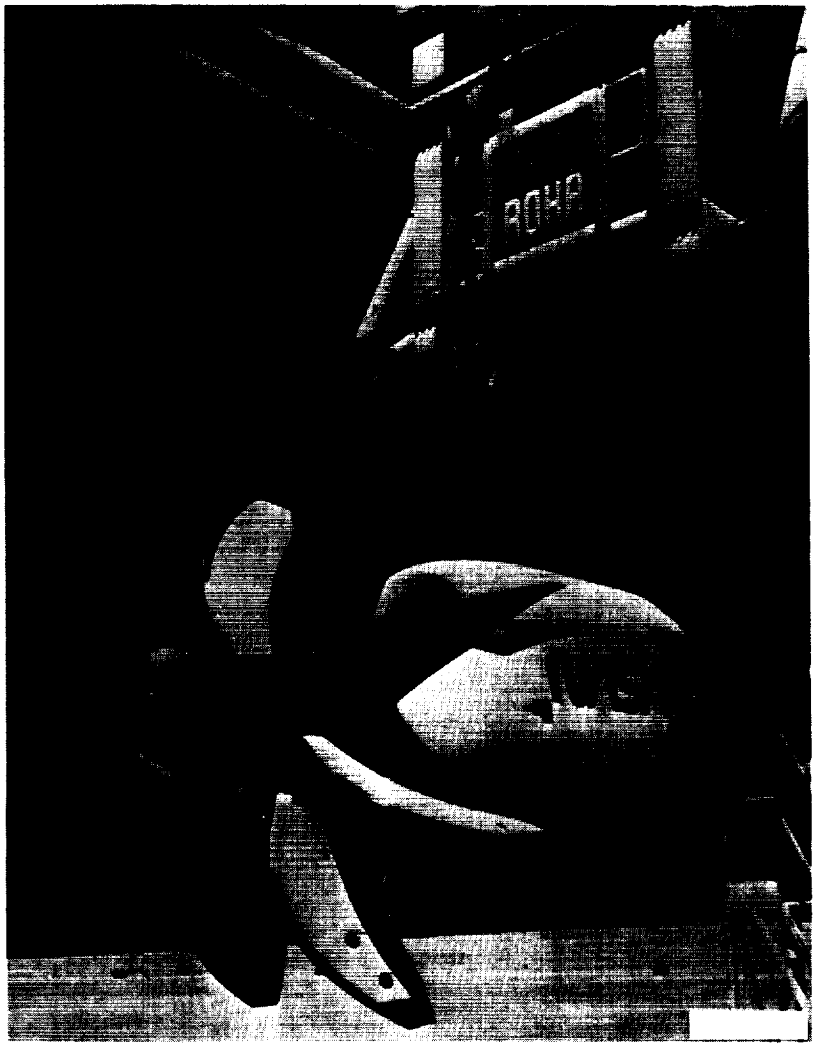

FIGURE 16. - ROHR PTA PROPULSION SYSTEM STATIC TEST.

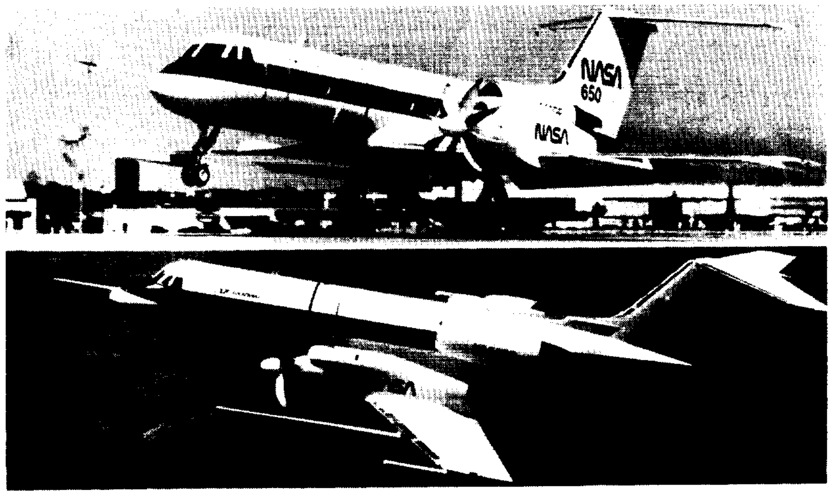

FIGURE 17. - PROPFAN TEST ASSESSMENT (PTA) FLIGHT TESTING.

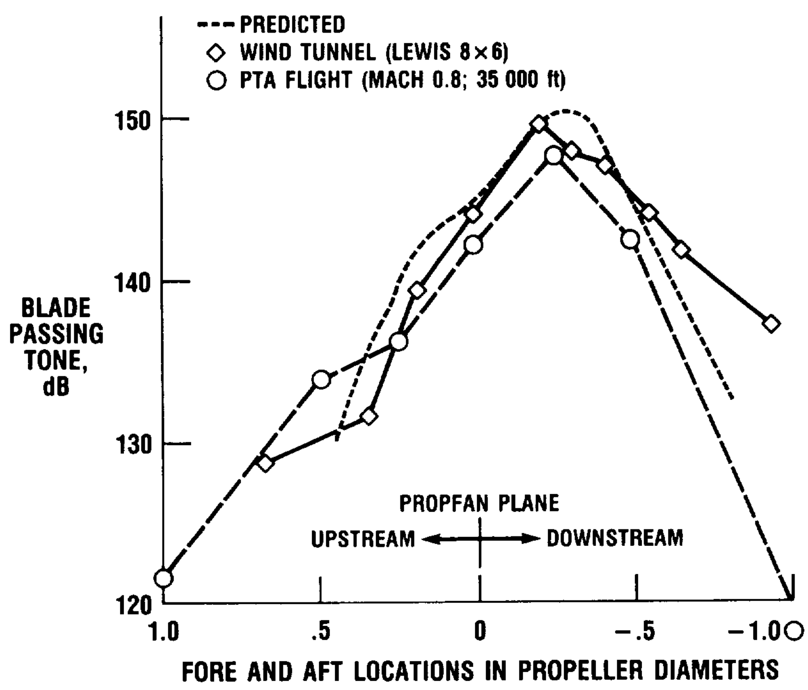

FIGURE 18. - COMPARISON OF PTA FUSELAGE SURFACE NOISE WITH PREDICTION AND WIND TUNNEL DATA.

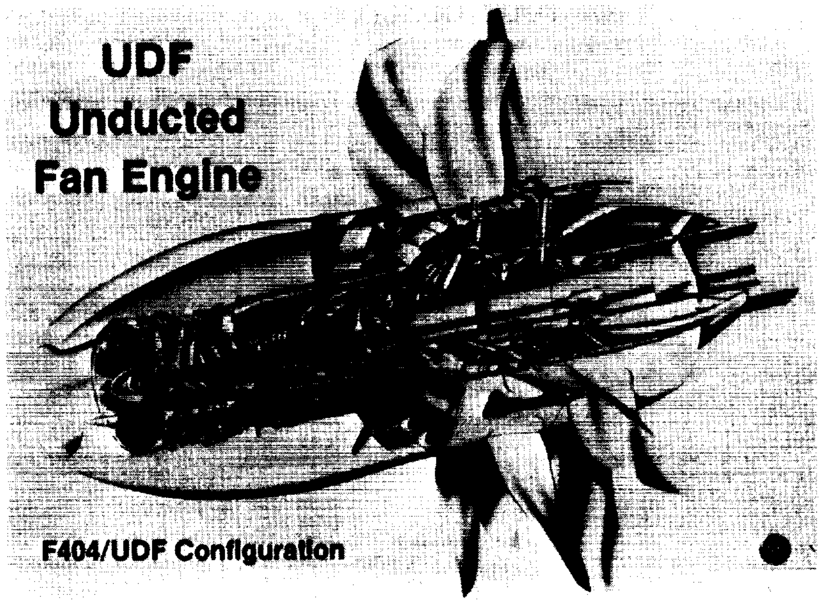

FIGURE 19. - UNDUCTED FAN ENGINE (UDF).

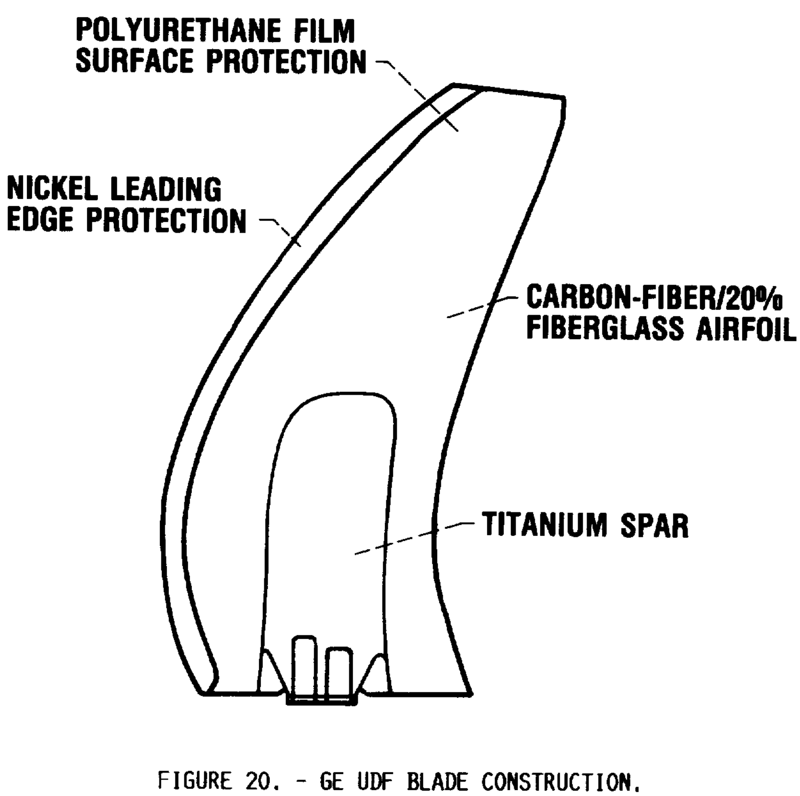

FIGURE 20. - GE UDF BLADE CONSTRUCTION.

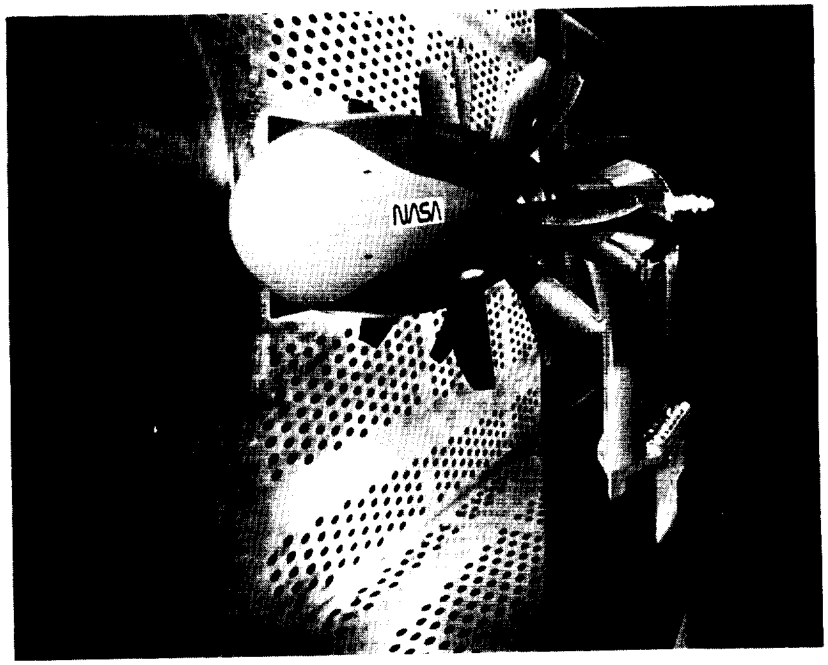

FIGURE 21. - UDF COUNTERROTATION PROPELLER MODEL IN NASA LEWIS 8- BY 6-FOOT WIND TUNNEL.

FIGURE 22. - WIND TUNNEL MODELS OF UDF COUNTERROTATION BLADE CONFIGURATIONS.

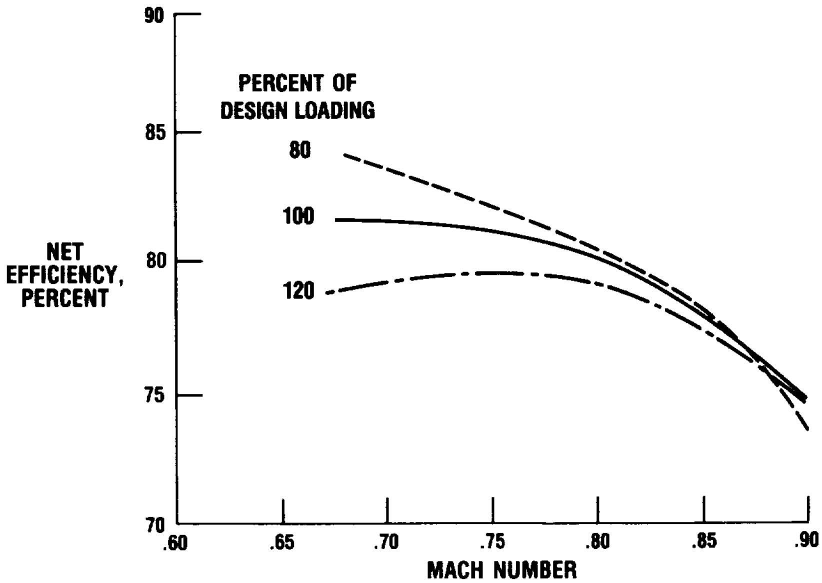

FIGURE 23. - F7-A7 UDF MODEL BLADE PERFORMANCE RESULTS. 8 + 8 BLADE CONFIGURATION, 780 FT/SEC TIP SPEED.

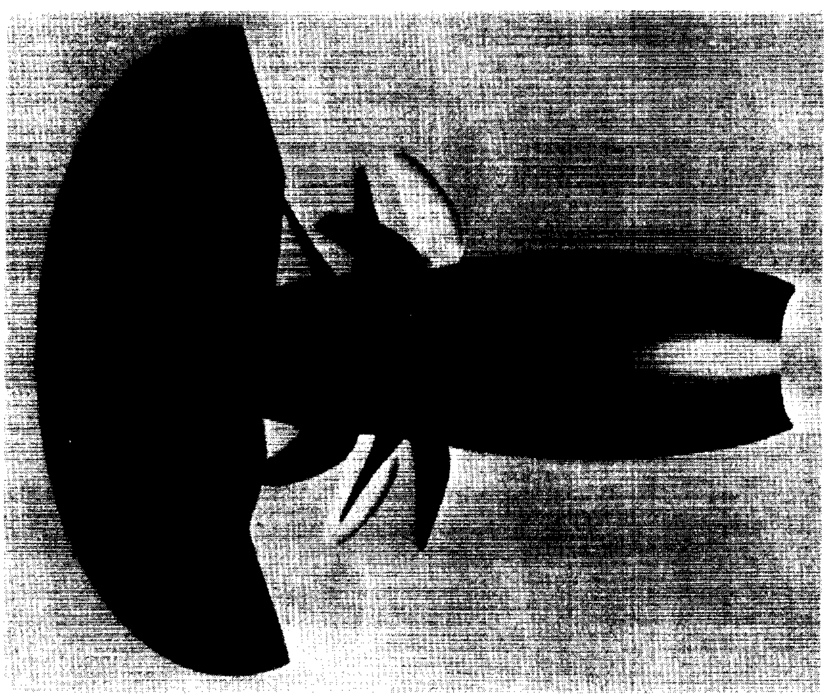

FIGURE 24. - THREE-DIMENSIONAL EULER ANALYSIS OF UDF PRESSURE DISTRIBUTION.

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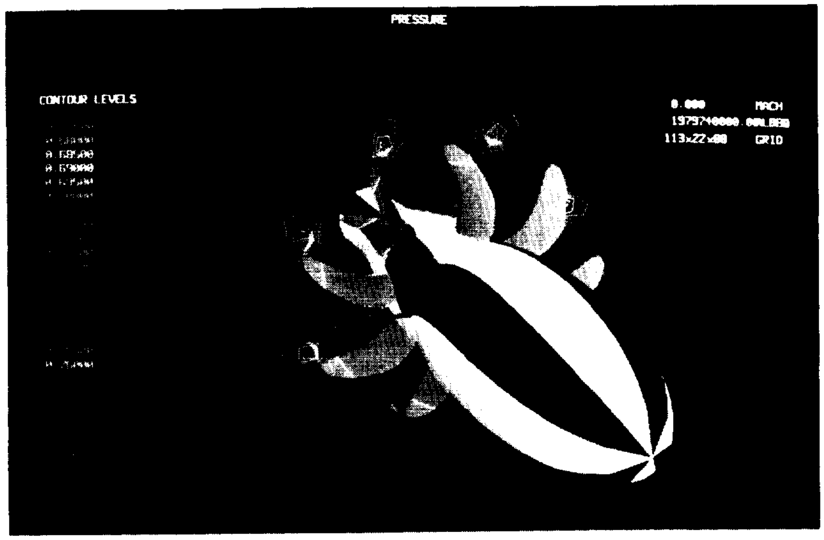
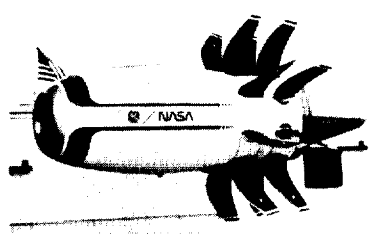
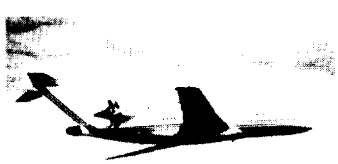


FIGURE 25. - UNSTEADY THREE-DIMENSIONAL EULER SOLUTION OF PRESSURE FIELD JUST DOWNSTREAM OF UDF AT ONE INSTANT IN TIME.



GE STATIC TEST AT PEEBLES, OHIO



BOEING 727 FLIGHT TEST

DOUGLAS MD-80 FLIGHT TEST

FIGURE 26. - NASA/GENERAL ELECTRIC UNDUCTED FAN ENGINE GROUND AND FLIGHT TESTING.

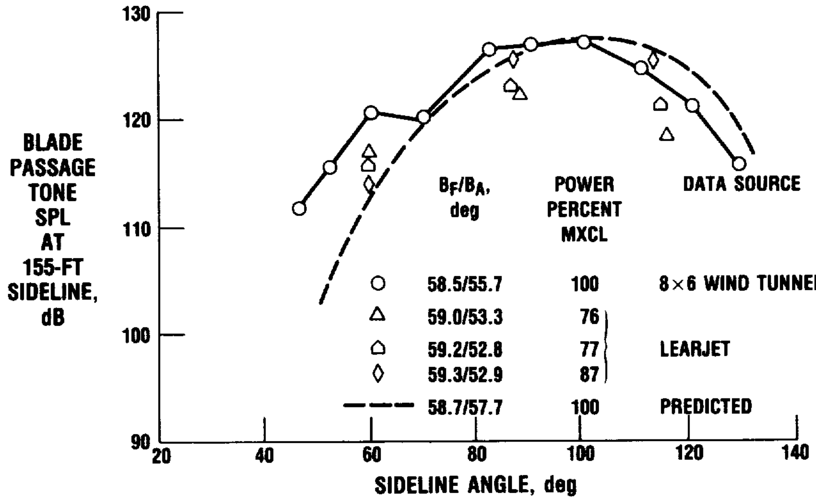


FIGURE 27. - UDF FUNDAMENTAL TONE DIRECTIVITY MEASURED IN FLIGHT, COMPARED WITH SCALED MODEL DATA AND PREDICTION. MACH 0.72 DESIGN SPEED.

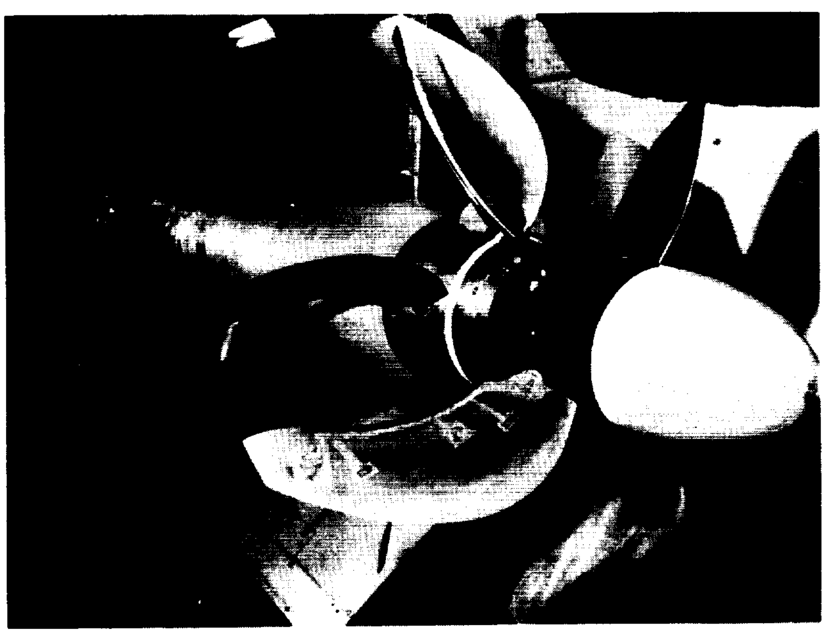


FIGURE 28. - HAMILTON STANDARD CRP-X1 COUNTERROTATION PROPFAN MODEL IN UTRC WIND TUNNEL.

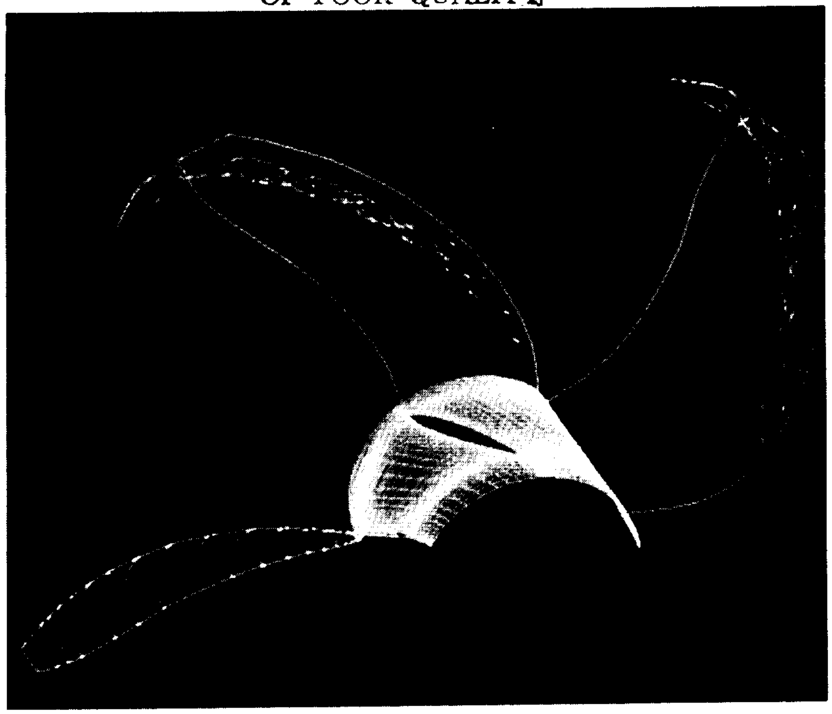


FIGURE 29. - NASA LEWIS PREDICTION CODE SIMULATES LEADING EDGE AND TIP VORTEX SHEDDING AT OFF-DESIGN MACH 0.2 CONDITIONS FOR CRP-X1 PROPFAN.

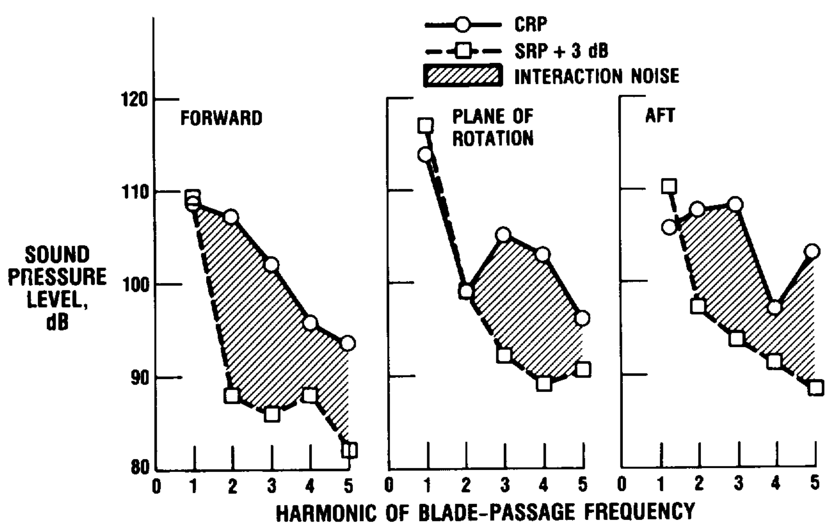


FIGURE 30. - CRP-X1 MODEL NOISE TEST DATA COMPARED WITH ADJUSTED SINGLE-ROTATION PROPFAN DATA.

FIGURE 31. - 1987 COLLIER TROPHY AWARDED TO LEWIS RESEARCH CENTER AND THE NASA/INDUSTRY ADVANCED TURBOPROP TEAM.

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15. Supplementary Notes

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16. Abstract

Experimental and analytical effort shows that use of advanced turboprop (propfan) propulsion instead of conventional turbofans in the older narrow-body airline fleet could reduce fuel consumption for this type of aircraft by up to 50 percent. The NASA Advanced Turboprop (ATP) program was formulated to address the key technologies required for these new thin, swept-blade propeller concepts. A NASA, industry, and university team was assembled to develop and validate applicable new design codes and prove by ground and flight test the viability of these new propeller concepts. This paper presents some of the history of the ATP project, an overview of some of the issues and summarizes the technology developed to make advanced propellers viable in the high-subsonic cruise speed application. The ATP program was awarded the prestigious Robert J. Collier Trophy for the greatest achievement in aeronautics and astronautics in America in 1987.

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